HOW TO OBTAIN DATA TO DO OBSERVATIONAL COSMOLOGY: AN EXAMPLE USING GRAVITATIONAL LENSING

PREVIOUS TALKS FOCUSSED ON ALL-IMPORTANT WHY ONE DOES OBSERVATIONAL COSMOLOGY.

THIS IS AN INTRODUCTION ON HOW ONE CAN GO ABOUT OBTAINING THE DATA!

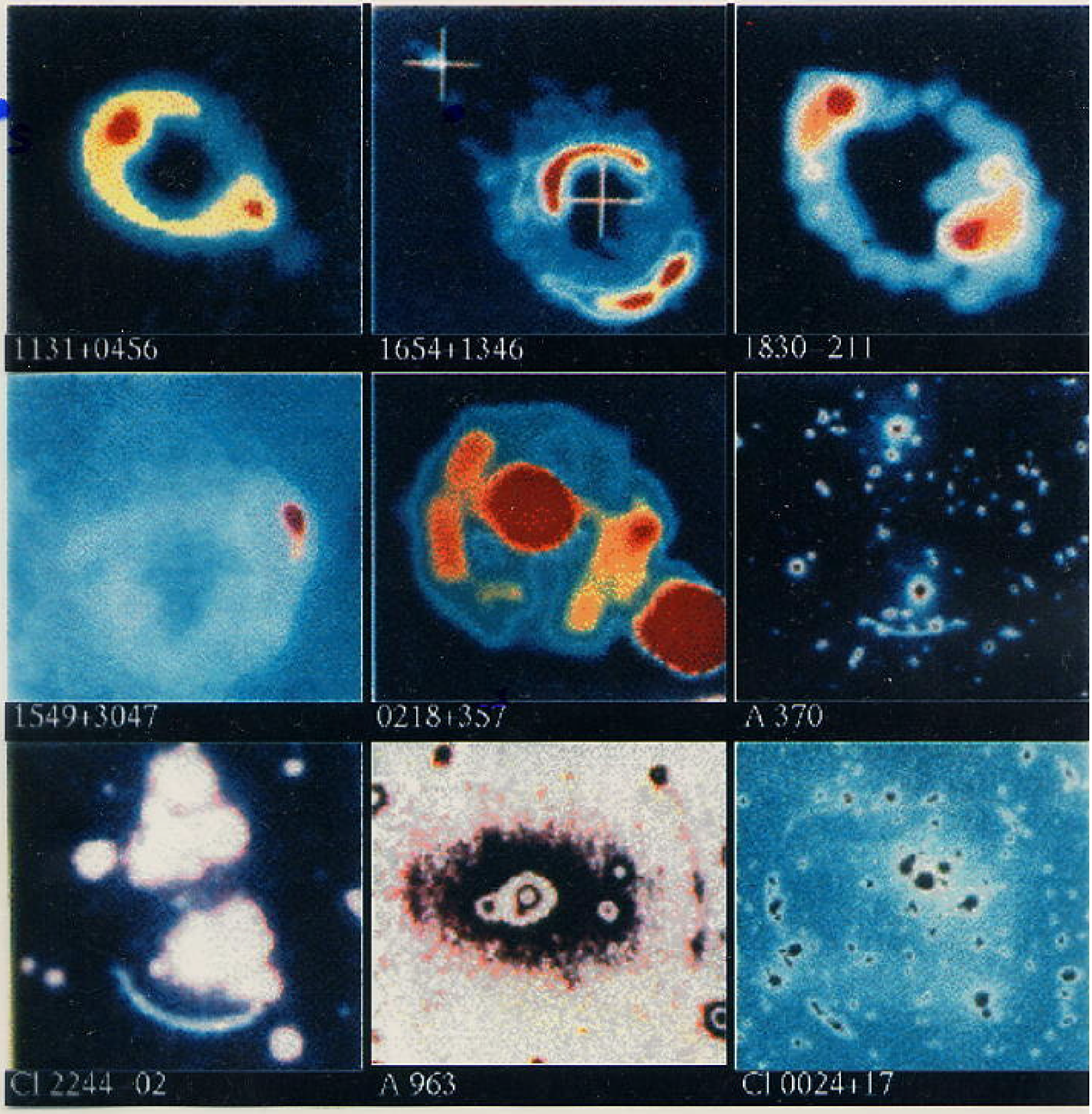
OUTLINE

I. INTRODUCTION: HISTORY, ZOO

II. OBSERVATIONS: PROCEDURE AND CALIBRATIONS

III. REDUCTIONS: IMAGES AND SPECTRA

IV. ANALYSIS: FOCUS ON BG-LIMITED CASES.


1131+0456
1654+1346
1830-211
1549+3047
0218+357
A 370
Cl 2244-02
A 963
Cl 0024+17

http: panisse. lbl. gov/~ bfrye

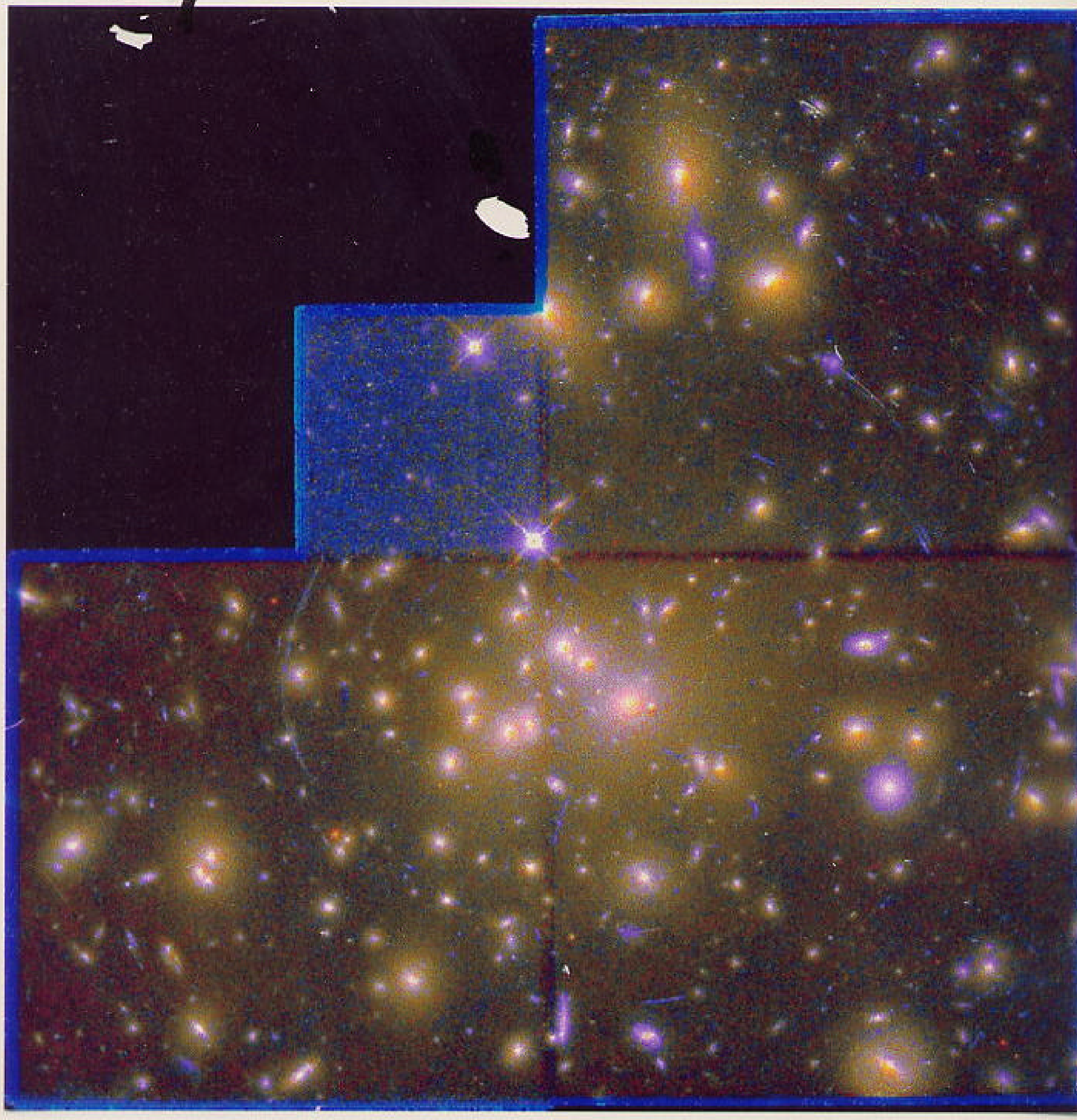
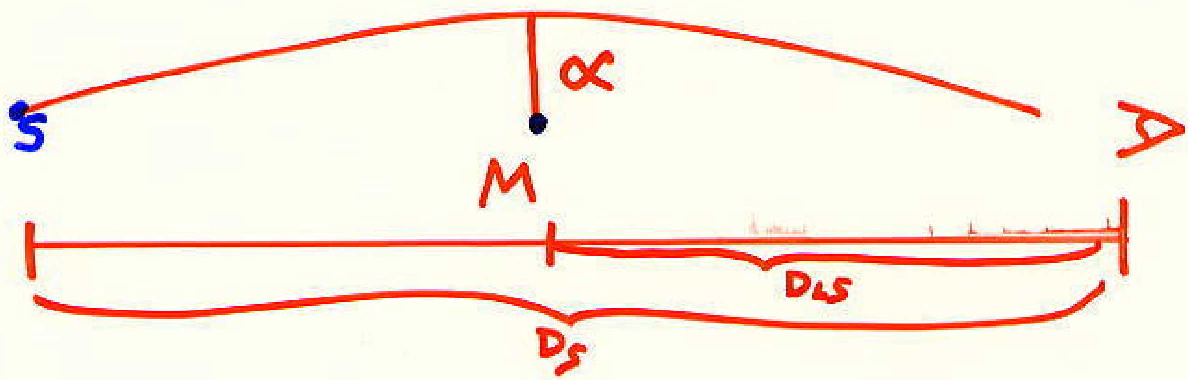


Fig. 1.— Color WFPC2 HST image of inner portion of A1689, at z=0.18.

$\bigcirc \xrightarrow[\delta]{} \oslash$

$\circ \xRightarrow[\mu]{} \bigcirc$

I. INTRODUCTION (a)



GRAVITATIONAL LENSING, OR BENDING OF LIGHT AROUND MASSIVE OBJECTS:

- PREDICTED BY EINSTEIN
- MEASURED BY OPPENHEIMER (2x)

MEASURING DEFLECTION α CAN GIVE THE MASS:

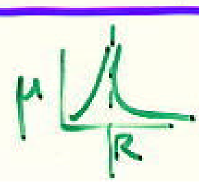
- POINT SOURCE, $\alpha \sim \frac{1}{b}$ b = impact parameter
- CANONICAL DISTRIBUTED ISOTHERMAL ~~SOURCE:~~ MASS

$$\alpha = 29'' \left(\frac{\sigma_v}{1000\,\mathrm{km/s}}\right)^2 \frac{D_{LS}}{D_S} \approx \text{constant}$$

(FOR A GIVEN SOURCE W/ A GIVEN LENS)

$\boxed{\text{SOURCES EVERYWHERE ARE DEFLECTED BY THE SAME AMOUNT!}}$

BUT



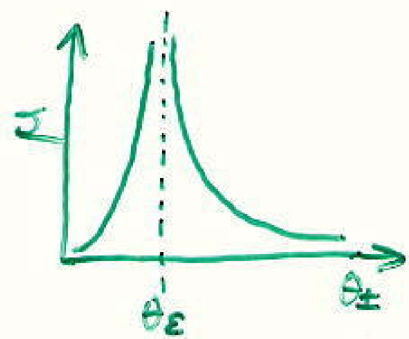
DISTRIBUTED ISOTHERMAL MASSES

(GALAXY CLUSTERS)

WHILE SOURCES MAY BE EQUALLY DEFLECTED, BY $\underline{\underline{\alpha}}$, THIS DOES NOT MEAN THAT THEY ARE EQUALLY-MAGNIFIED!

MAGNIFICATION ($\underline{\mu}$) IS THE RATIO OF LENSED TO UNLENSED IMAGE AREAS, WHICH FOR AN ISOTHERMAL SPHERE IS:

$$\mu = \frac{a}{b} = \frac{\theta_I}{\theta_S}, \because \theta_I = \theta_S + \theta_E \Rightarrow \mu = \frac{1}{|1 \pm \theta_E/\theta_S|}$$



FINALLY, SURFACE MASS DENSITY $\underline{\underline{\Sigma}}$ DETERMINES LARGELY THE CONDITION FOR LENSING MASSES SUCH AS GALAXY CLUSTERS, AND DETERMINES CONDITION FOR GIANT ARCS

$$\Sigma > \Sigma_{CR} = 0.35\ g/cm^{-2} \left(\frac{D}{Gpc}\right)^{-1}, \quad D = \frac{D_{LS} D_L}{D_S}$$

GRAVITATIONAL LENSING

IT RESPONDS TO TOTAL GRAVITATIONAL POTENTIAL, AND CAN BE MEASURED OVER A BROAD RANGE OF MASSES, MAKING IT A VERY POWERFUL TOOL FOR COSMOLOGY. FINE, BUT WHAT KIND OF DATA DO YOU NEED?

$0.001 - 1 M_\odot$ PLANETS/STELLAR-SIZED OBJECTS

- MICROLENSING (MACHO, OGLE)

$\Rightarrow$ REQUIRES IMAGES + CONFIRMING SPECTRA.

$\sim 10^{10} - 10^{11} M_\odot$ GALAXY-SIZED OBJECTS

- GALAXY-GALAXY (STATISTICAL) (DISTORTION)
- QSO-GALAXY (TIME DELAY) (HDF)

$\Rightarrow$ REQUIRES PRIMARILY IMAGING

$> 10^{12} M_\odot$ GALAXY CLUSTERS/SUPERCLUSTERS ... LSS

- IMAGE DISTORTIONS
- REDSHIFTS

$\Rightarrow$ REQUIRES IMAGING + SPECTROSCOPY.

II. OBSERVATIONS

TARGET SELECTION: ESTABLISH CRITERIA SUCH AS FLUX, S/N, Z, COLOR etc. FOR EXAMPLE, USE COLOR-MAGNITUDE DIAGRAM TO SELECT BACKGROUND OBJECTS TOWARDS CLUSTERS.

PREPARATION:

ASTROMETRY: (NEED TO TELL TELESCOPE WHERE TO POINT!)

OFFSETS: WHERE ARE THE OFTEN FAINT TARGETS WRT BRIGHTER ONES THAT YOU CAN SEE IN THE FINDER CAMERA?

SIGNAL-TO-NOISE (S/N): FOR BACKGROUND-LIMITED CASES, $\boxed{S/N \sim (T/S)^{1/2}}$, WHERE T = EXPOSURE TIME, AND S = SKY NOISE. HOW LONG TO EXPOSE TO GET DESIRED S/N.

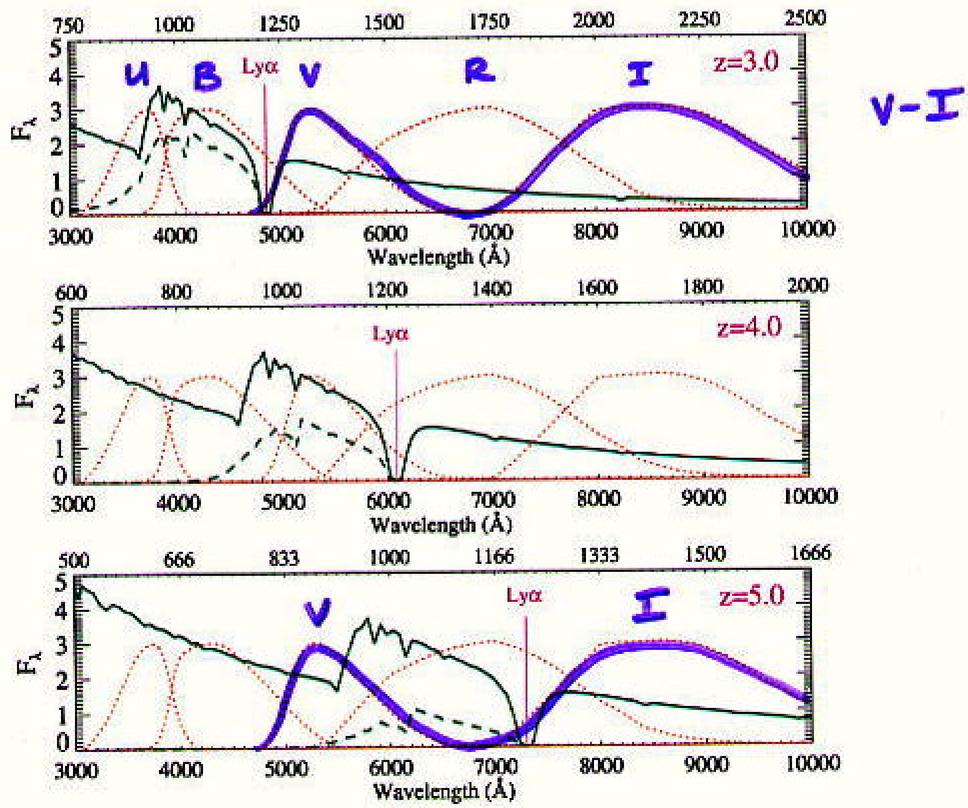


Figure 6.1: Model spectra of the $z = 4$ galaxy for a stellar population dominated by B3 stars for three different z's. F_λ is plotted against observed wavelength on the lower axis and rest wavelength on the upper axis. The solid line gives the model spectrum, including HI absorption at the source. The model given by the dashed line shows the effect of the z-dependent Lyman-series forest opacity. The five dotted continuous curves give the transmission curves for the $UBVRI$ filters, in order of increasing wavelength.

ARCLET REDSHIFT SURVEY: SELECTION

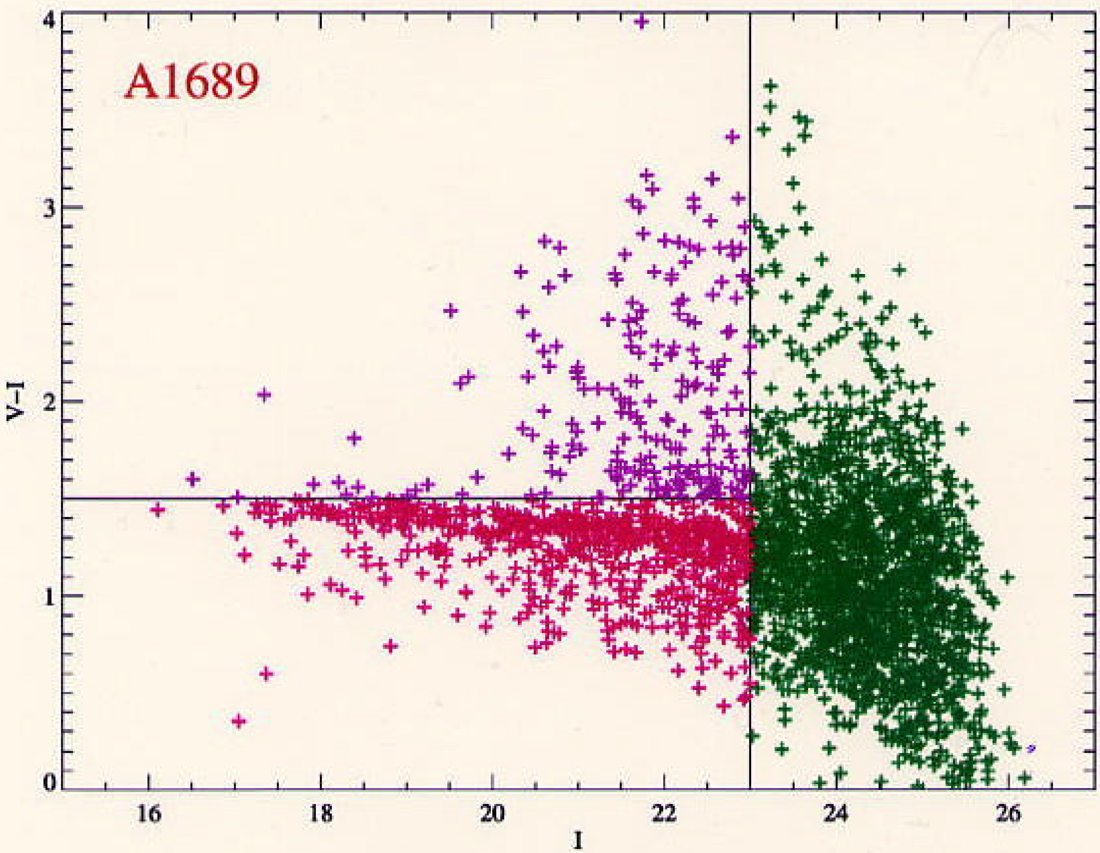
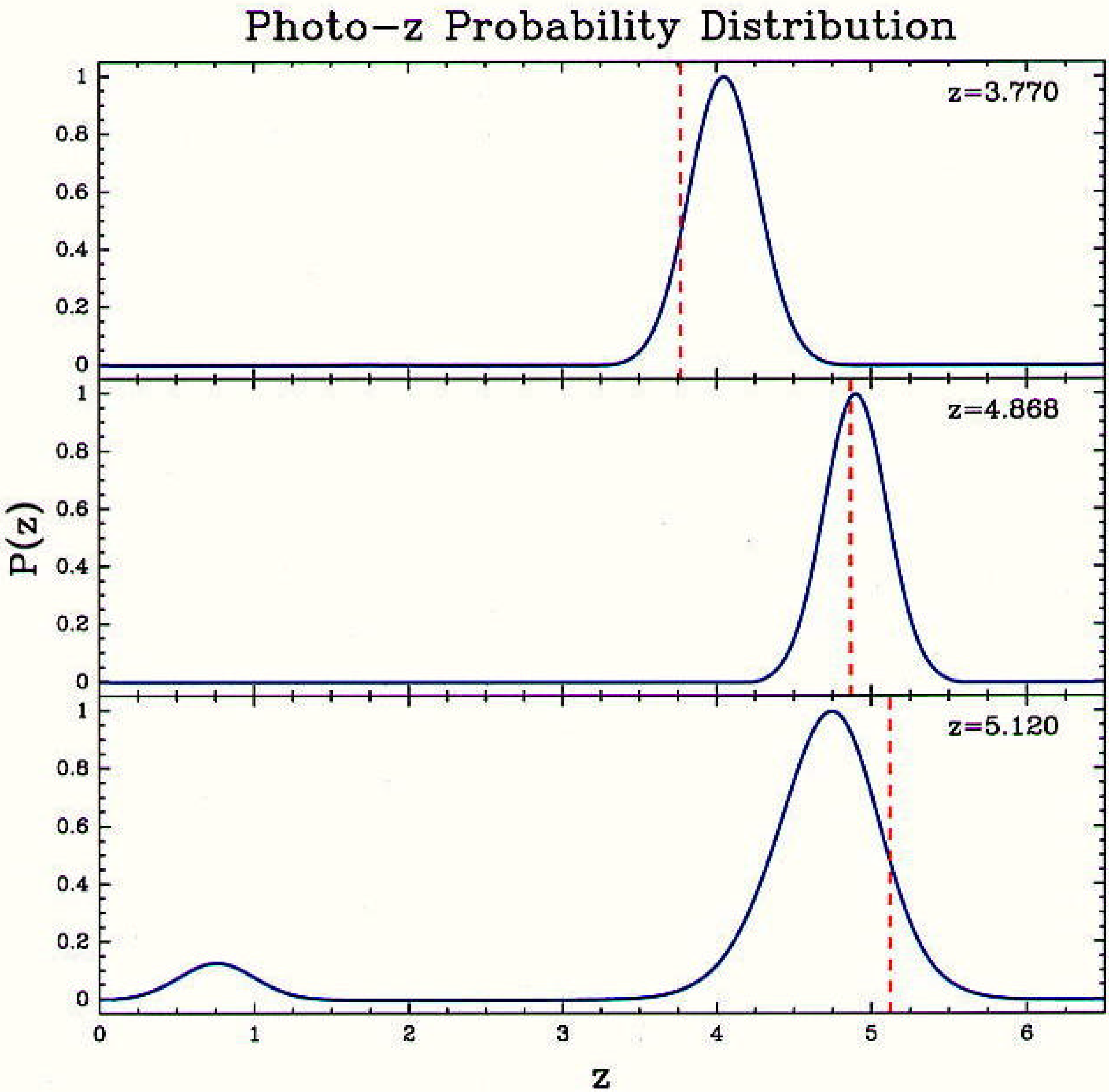


Figure 1. Color magnitude diagram for the cluster A1689. The sample is complete to $I = 23$ and the targets color-selected to be behind the cluster ($V - I = 1.5$). The rougly-horizontal concentration of points just below the color cut is the cluster sequence.

FLUX-LIMITED, $I < 23$ RED-SELECTED, $V - I > 1.5$ ONLY


Photo−z Probability Distribution
z=3.770
z=4.868
z=5.120
P(z)
z
0
0.2
0.4
0.6
0.8
1
1
2
3
4
5
6

2. OBSERVATIONS

OBSERVING PROCEDURE

BIAS ⇒ CONSTANT PEDASTAL WHICH CAN BE SUBTRACTED OFF.

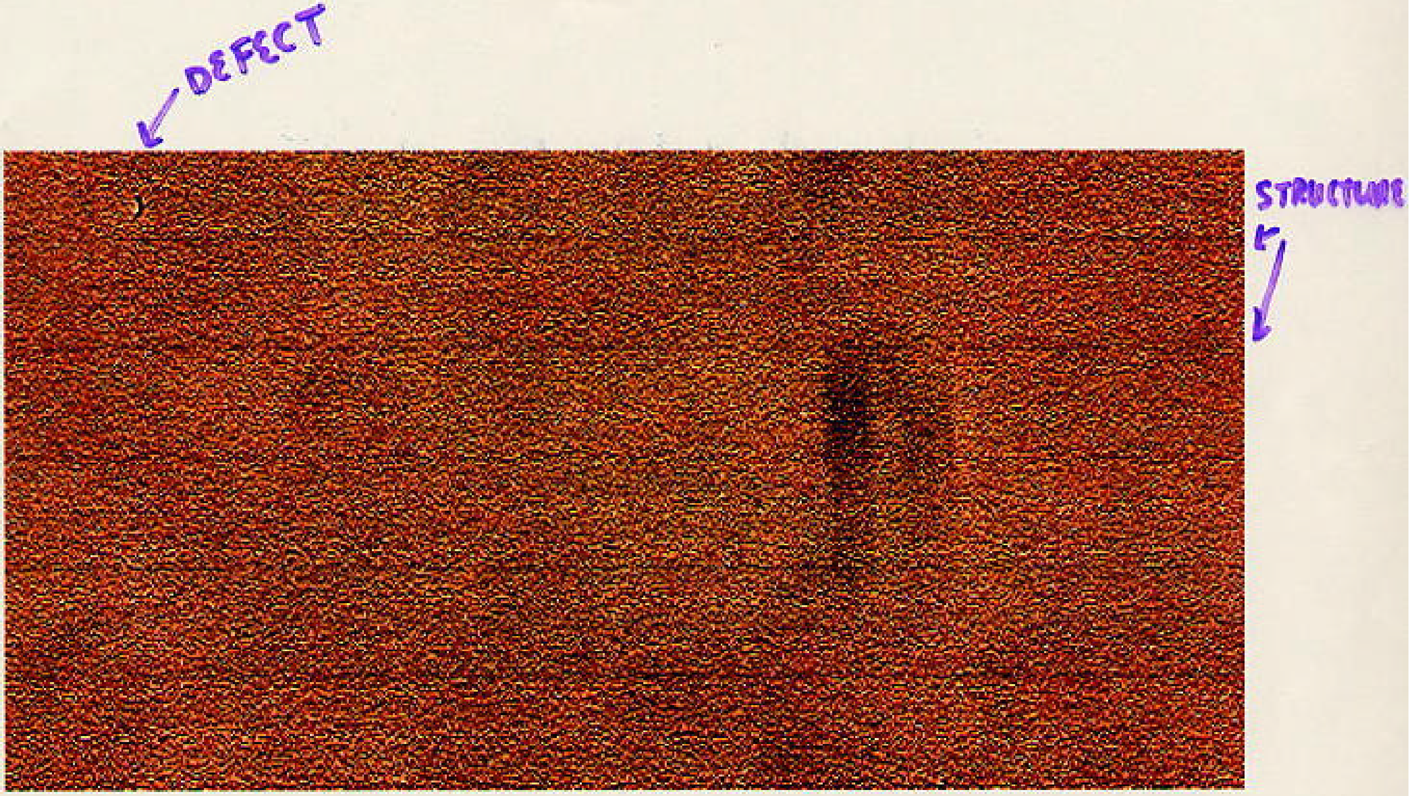
FLATFIELD OR "SUPERFLAT" ⇒ FOR REMOVING PIX TO PIX VARIATIONS
- TRAIN A LIGHT ON THE DOME.
- COMBINE IMAGE FRAMES SANS SOURCES "SUPERFLAT"

DISPERSED FLATFIELD ⇒ FOR REMOVING λ-DEPENDENT PIX to pix VARIATIONS.

STANDARDS ⇒ FLUX AND SPECTROPHOTOMETRIC. OR HOW TO GO FROM COUNTS ON CCD TO A MEASUREABLE FLUX.

DATA!

FLAT FIELD



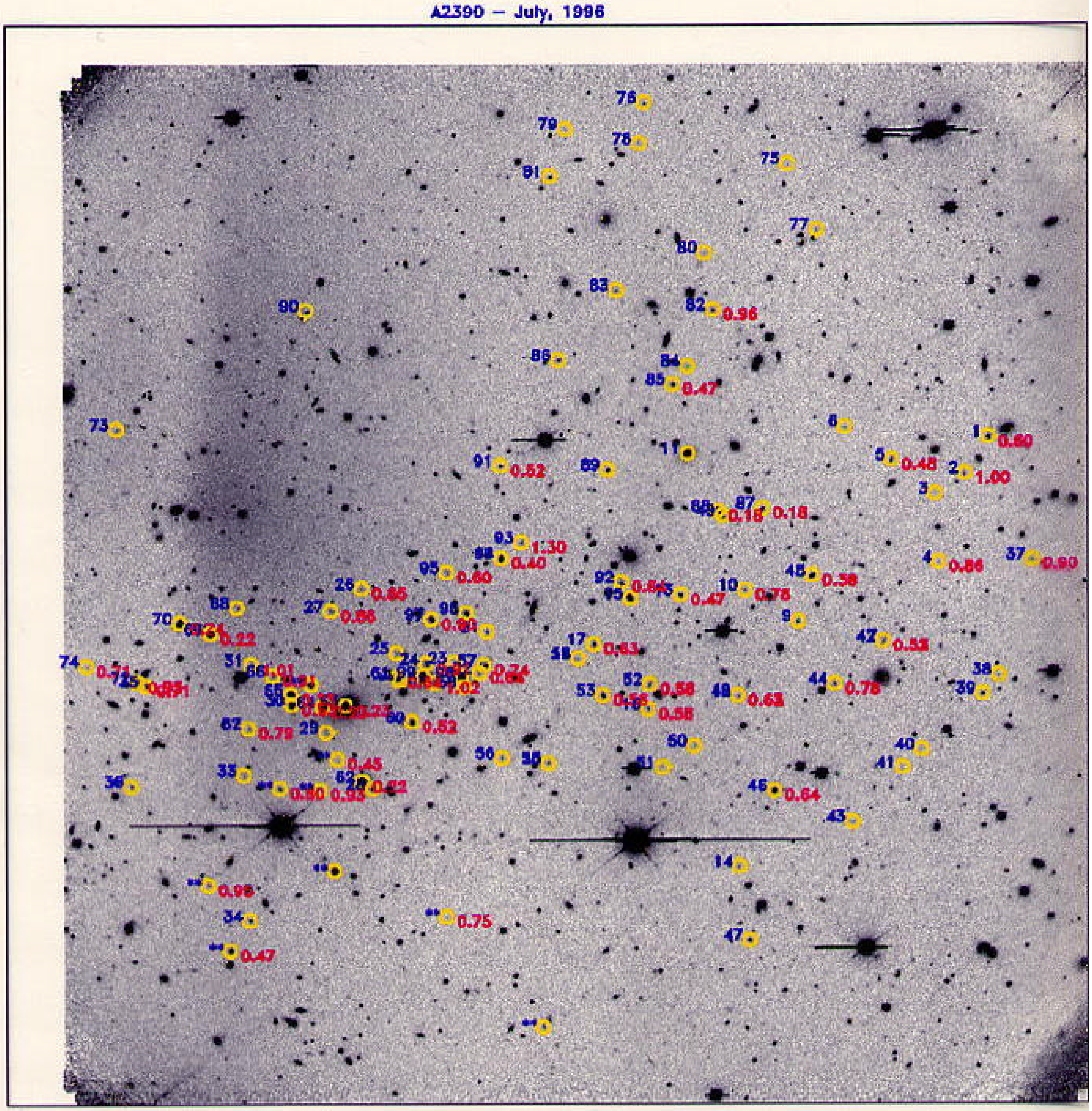


Fig. 1.— I band CFHT image of A2390, at z=0.22, with targets labelled.

3. REDUCTIONS : INTERESTING!

MAINLY CONCERNED WITH CCD'S (X-ray → IR).

→ SUBTRACT BIAS

→ FLATTEN (DIVIDE BY DOME FLAT).

→ OBTAIN BEST ESTIMATE OF BACKGROUND, AND SUBTRACT. MUST ELIMINATE COSMIC RAYS AND ACCOUNT FOR IMAGE DISTORTIONS.

CURVATURE (ARTEFACT OF FLAT DETECTOR ON A CURVED FOCAL PLANE).

SPECTRAL TILT RELATED ARTEFACT.

→ WAVELENGTH CALIBRATE : ASSIGN λ's to PIXELS USING "FREE" ATMOSPHERIC LINES AND/OR ARCS.

→ CORRECT FOR CTE : POSITION, BACKGROUND, FLUX, TIME..

→ FLUXING. APPLY STANDARDS.

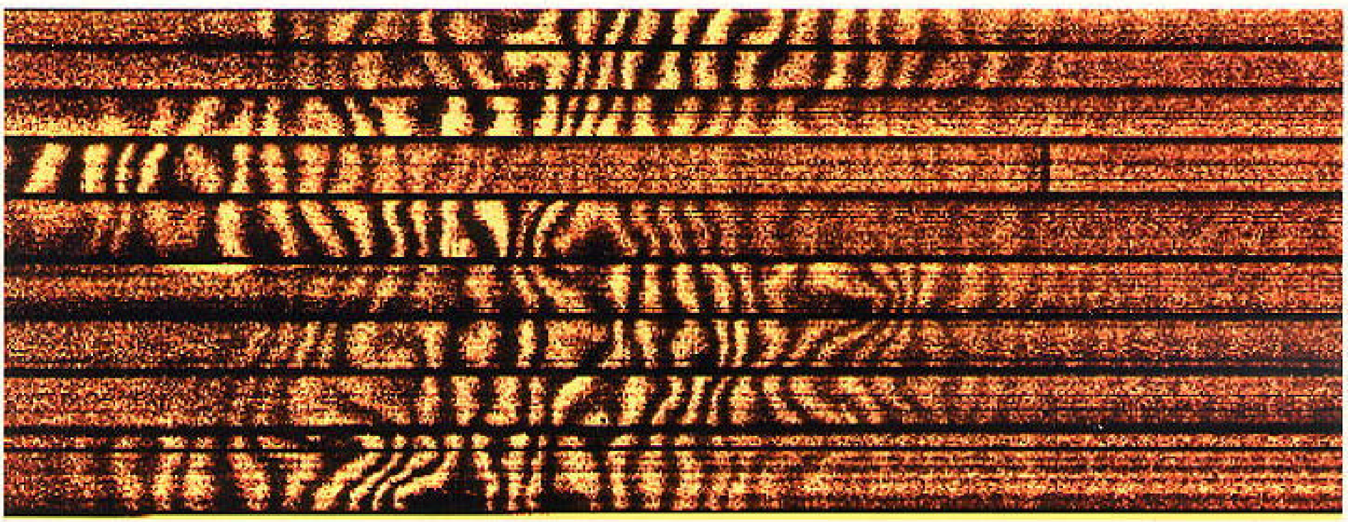
OTHER: FRINGING, SLIT FUNCTION.

DISPERSED FLATFIELD

SLIT IS NOT PERFECTLY RECTANGULAR! slit

UNEVEN ILLUMINATION PRODUCES DARK + BRIGHT STRIATIONS. THIS SLIT FUNCTION IS COMPLEX, BUT CAN BE CORRECTED FOR W/ KNOWLEDGE OF THE <u>CURVATURE</u>. ~spectrum

SPATIAL →

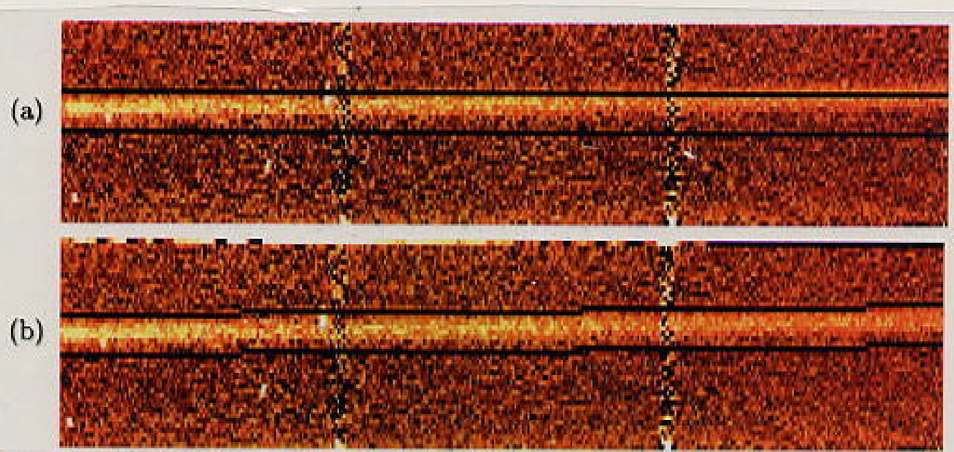


DISPERSION →

HORIZONTAL DARK STREAKS ARE ARTEFACTS OF THE SLIT FUNCTION.

PATTERN IS CCD FRINGING. IT'S TIME VARYING AND WAVELENGTH DEPENDENT.

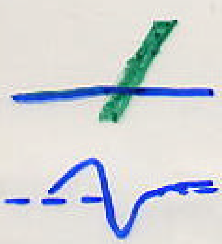
CURVATURE: SPATIAL AND SPECTRAL



AIM IS TO AVOID REPIXELIZATION, SO EVERY COHERENT PATTERN OF PIXELS HAS A CHANCE OF BEING DETECTED IN THE FINAL IMAGE.

SPATIAL: CURVED FOCAL PLANE INTRODUCES CURVATURE, 3-5 PIXELS FROM CENTER TO EDGE.
FIT LOW ORDER POLYNOMIAL TO OBTAIN CURVATURE
→ AVOID REPIXELIZATION!

SPECTRAL: SPATIAL DEPENDENCE ON THE WAVELENGTH.
FIT A SMOOTHLY-VARYING 2d SURFACE.
⇒ AVOIDS REPIXELIZATION!



ARCLET REDSHIFT SURVEY: SPECTROSCOPY

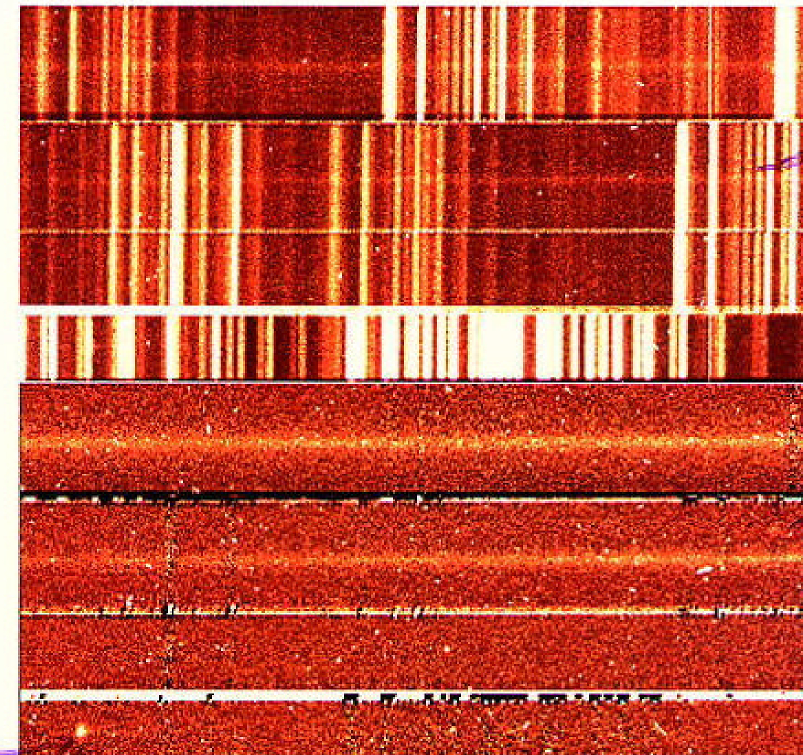


Figure 4.4: Comparison of frames before and after background subtraction over the same 2d spectral region. Sample regions from four different spectra are shown here, each covering a different wavelength range. The dispersion direction is left-right and the spatial direction is up-down. Note that there is an emission line object in the lower left-hand corner which is only made obvious after the background subtraction. This is Lyα at 7418 Åand $z = 5.12$. The redshift of the other emission line object in this field, in the upper right hand side of the image, has yet to be determined. Note the general smoothly-distributed noise of the subtracted background and the inevitable skyline residuals

MAXIMIZE # ARCLETS PER MASK

TO COPE WITH THE LARGE NUMBER OF SPECTRA, & TO HAVE CONTROL OVER THE SYSTEMATICS, WROTE A COMPLETE REDUCTION PACKAGE.

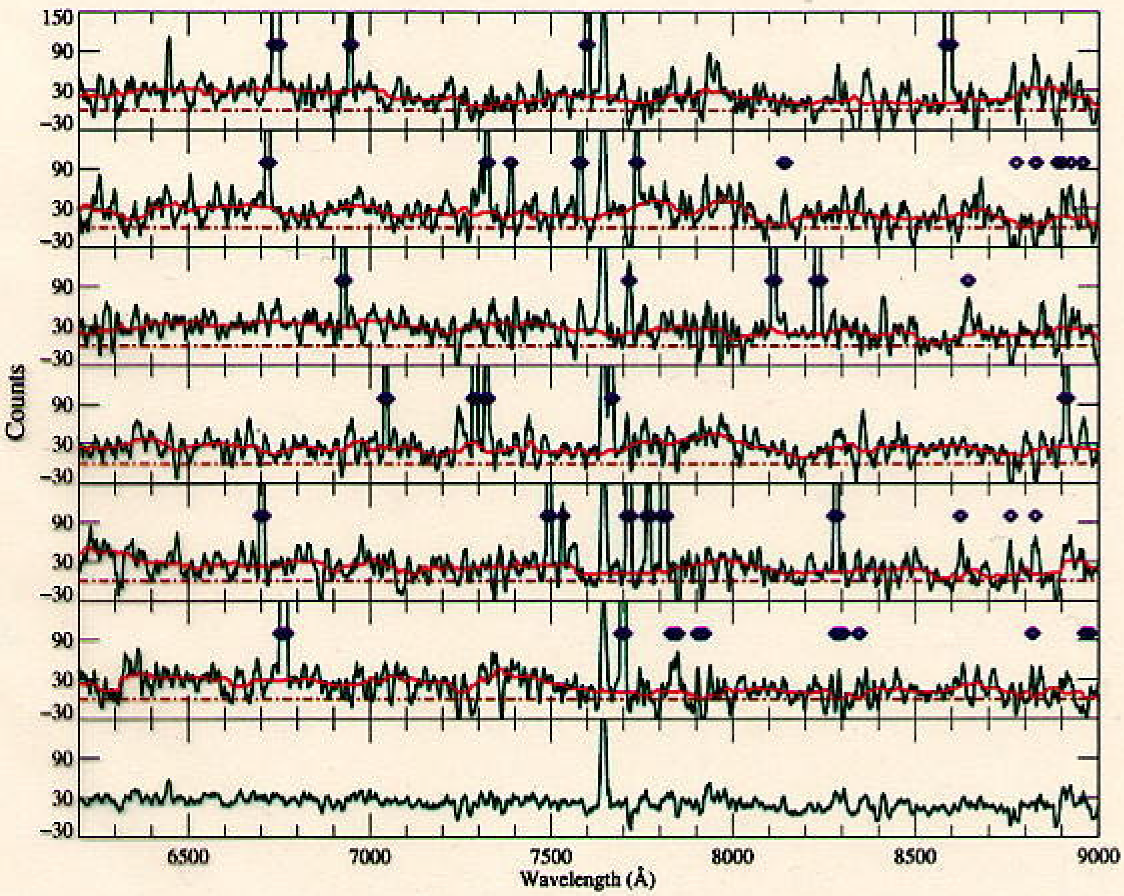


Figure 4.7: The 'spadd' spectral coaddition task output. This is a multi-panel plot of counts vs. observed wavelength for each of the 6 exposures of this particular spectrum, and the seventh panel (bottom) gives the result of the coaddition. The continuum level is marked by the solid line, against which high and low deviant points are flagged (diamond points). The dot-dashed line marks the zero level of the continuum.

4. ANALYSIS

CAN TAKE MANY DIRECTIONS. LET'S FOCUS ON THE MOST BACKGROUND - LIMITED CASES TO DEMONSTRATE THE SUBTLETY INVOLVED (BUT NOT COMPLETELY-SOLVED)!

- IMAGES ARE FAINT
- S/N IN SPECTRA LOW ($\sim 3\sigma$)

⇒ YET THESE ARE REAL HIGH-Z OBJECTS (MOSTLY), AND ONE CAN DO REAL PHYSICS.

- OUTFLOWS (PROBABLY ESCAPE GALAXY POTENTIAL)
- EVOLUTION OF STELLAR CONTINUA (PROMISING EVIDENCE OF STAR FORMATION TRACER GROWING WITH TIME BUT NEED MORE DATA)
- SMALL SIZES (CONSEQUES OF MORPHOLOGY PLUS PRESENCE OF LARGE OUTFLOWS)

CONCLUSION: THE "WHY" GETS US THE FUNDING BUT IT'S THE "HOW" THAT GIVES US SOMETHING TO DO.

BROADHURST, HUANG, FRYE, ELLIS 2000
$z = 1.675$
$M = 1.1 \times 10^{14} M_{\odot}/h$ $(\Omega = 1)$
$M/L = 320\, h\, (M/L_B)_{\odot}$

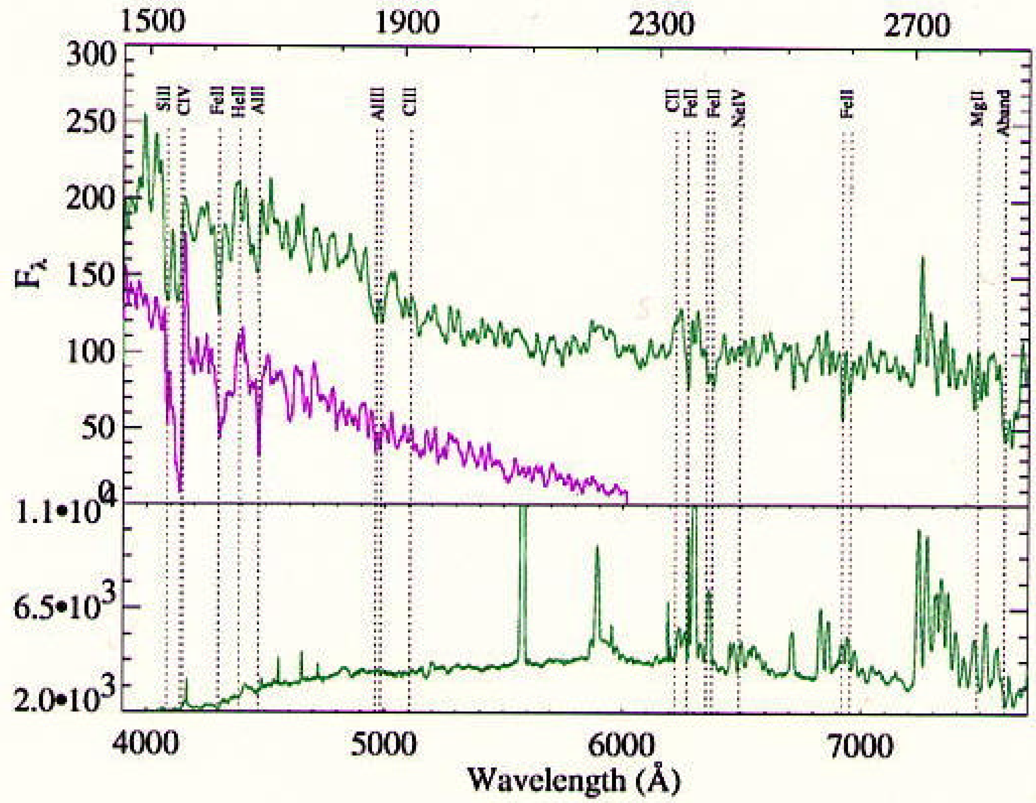


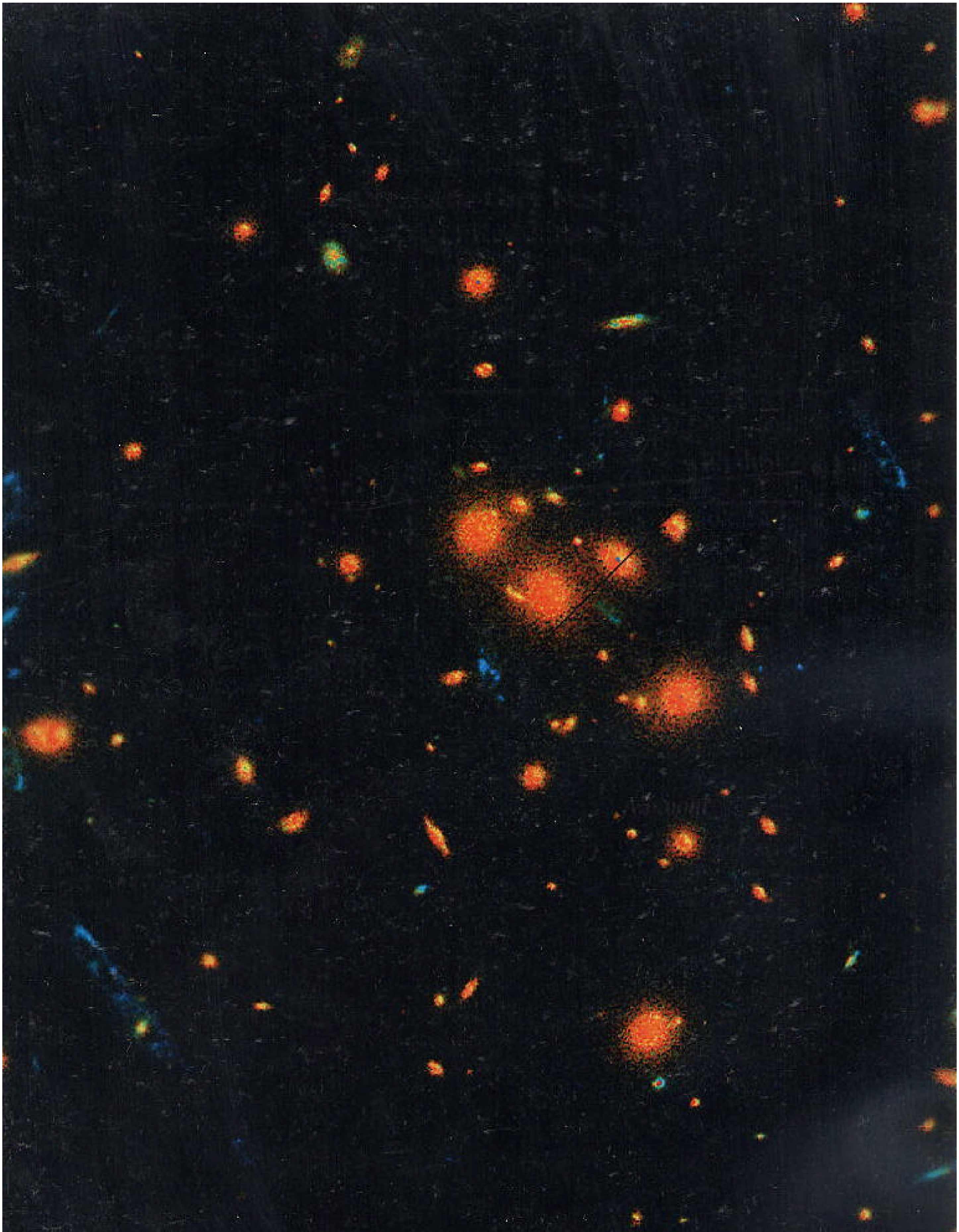
Figure 5.5: The upper curve is the fluxed spectrum of the upper HII region of arc C (fig 2b). Many weak absorption lines are visible yielding an unambiguous redshift of z=1.675. Note the similarity with the local "Wolf-Rayet" galaxy (lower curve) NGC4214 (Leitherer et al., 1996). The sky spectrum is also shown, in the lower panel

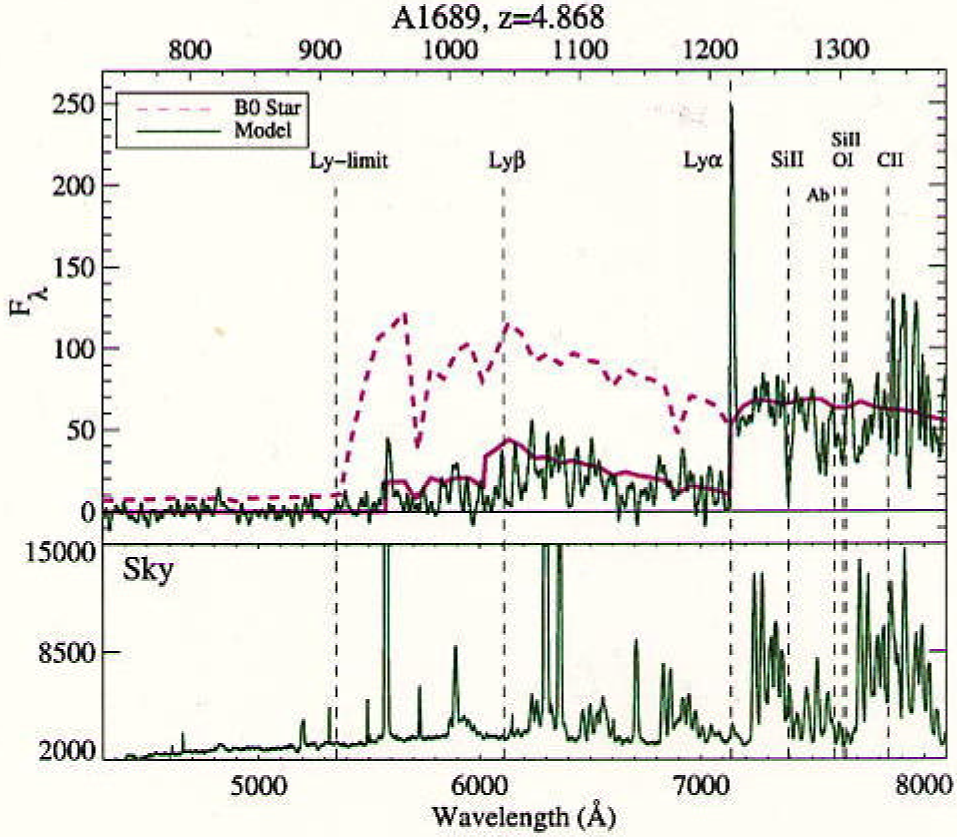
substructure is in excess of N-body predictions which, as Ghigna et al. (1998) point out are underestimates withint the central $50kpc/h$, where the problem of 'overmerging' is still significant.

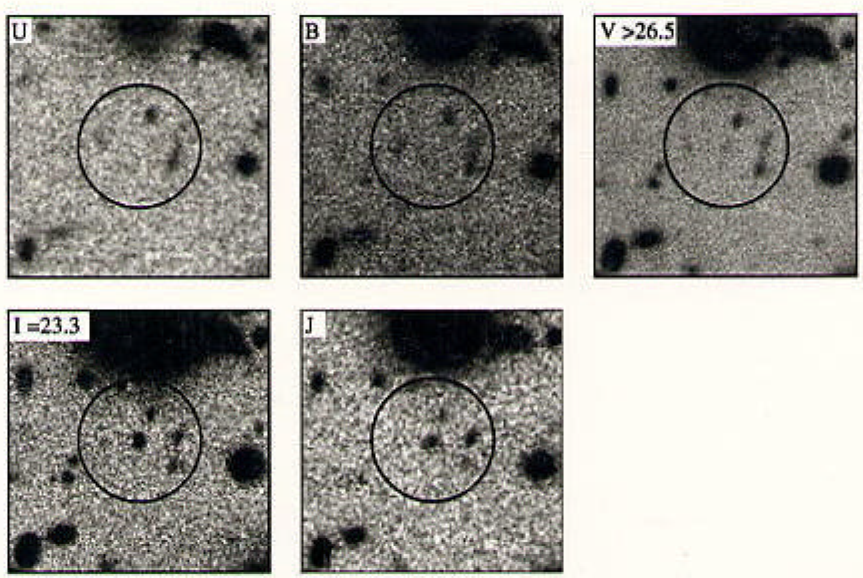
5.1.4 MS2137

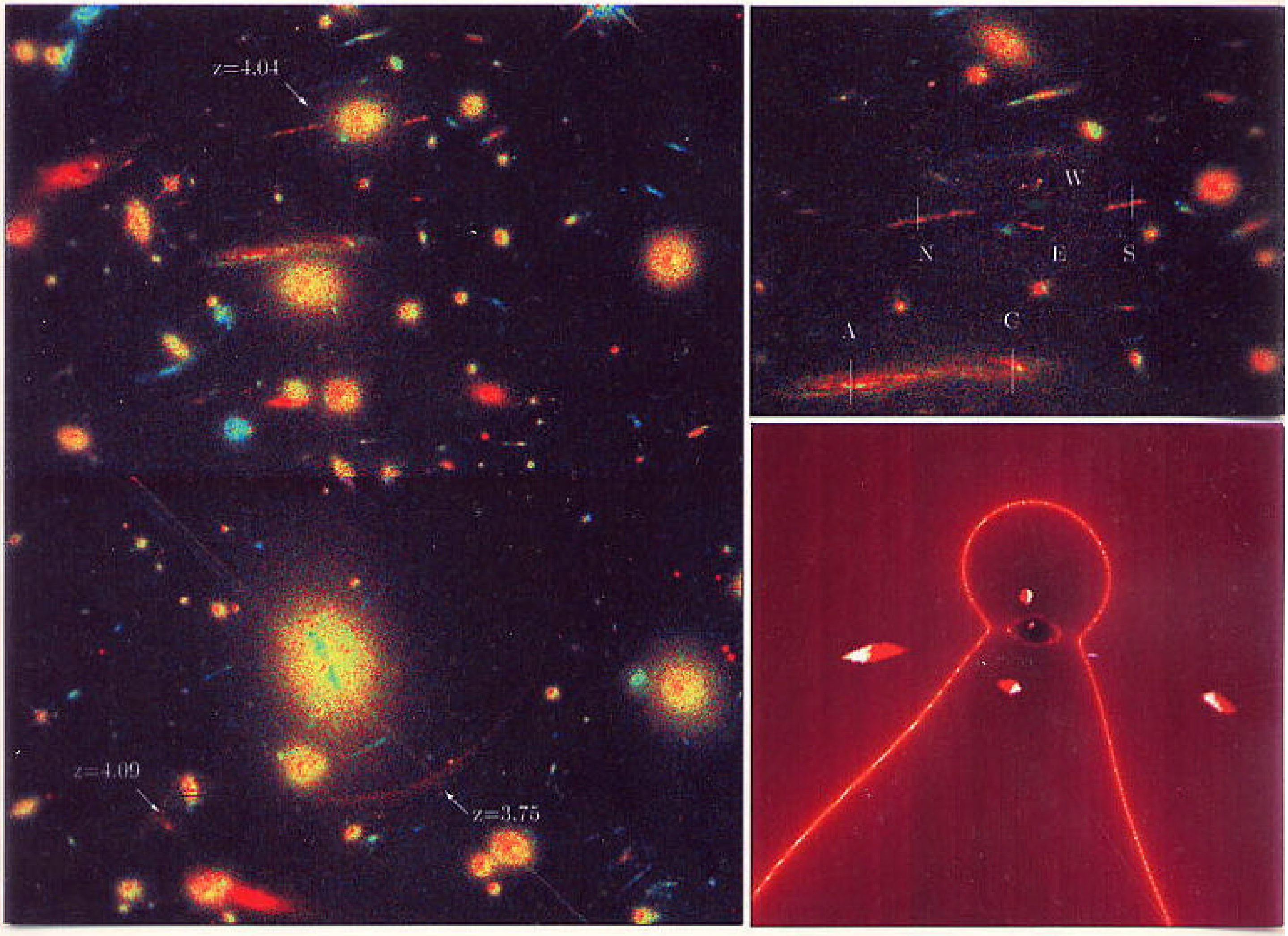
Fig. 5.7 shows an HST R band image of the central arcminute of the cluster MS2137. Note the two parallel giant arcs just below and to the left of the central cluster galaxy, and the radial arcs as well. This is probably one of the best examples of radial arcs, of interest to lens modelling for determining accurate cluster caustics (ref?).

A spectrum of this giant tangential arc appears in Fig. 5.8, where counts are plotted vs. observed wavelength on the bottom axis and rest wavelength on the top axis. The sky spectrum appears in the lower panel for comparison. The redshift fhas yet to be determined, but it is probably the highest signal-to-noise spectrum taken of this arc and so

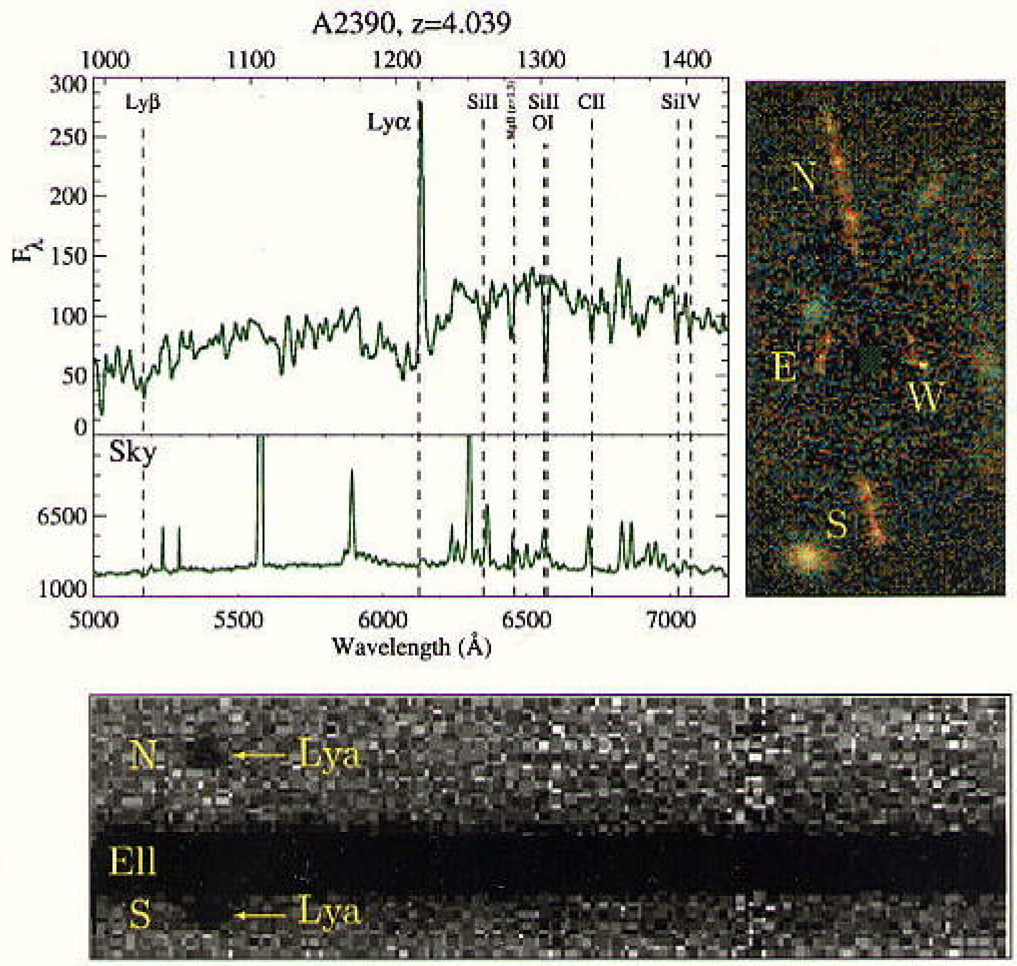



A1689, z=4.868
800
900
1000
1100
1200
1300
B0 Star
Model
Ly–limit
Lyβ
Lyα
SiII
SiII
OI
CII
Ab
F_λ
250
200
150
100
50
0
15000
Sky
8500
2000
5000
6000
7000
8000
Wavelength (Å)


U
B
V >26.5
I =23.3
J



FRYE + BROADHURST '9


A2390, z=4.039
1000
1100
1200
1300
1400
300
250
200
150
100
50
0
F_λ
Lyβ
Lyα
SiII
SiII
OI
CII
SiIV
Sky
6500
1000
5000
5500
6000
6500
7000
Wavelength (Å)
N
E
W
S
N
Lya
Ell
S
Lya